

Origin of ‘end of aging’ and sub-aging scaling behavior in glassy dynamics

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Linear response functions of aging systems are routinely interpreted using the scaling variable t_{obs}/t_w^μ , where t_w is the time at which the field conjugated to the response is turned on or off, and where t_{obs} is the ‘observation’ time elapsed from the field change. The response curve obtained for different values of t_w are usually collapsed using values of μ slightly below one, a scaling behavior generally known as *sub-aging*. Recent spin glass Thermoremanent Magnetization experiments have shown that the value of μ is strongly affected by the form of the initial cooling protocol (Rodriguez et al., Phys. Rev. Lett. 91, 037203, 2003), and even more importantly, (Kenning et al., Phys. Rev. Lett. 97, 057201, 2006) that the t_w dependence of the response curves vanishes altogether in the limit $t_{\text{obs}} \gg t_w$. The latter result shows that the widely used t_{obs}/t_w^μ scaling of linear response data cannot be generally valid, and casts some doubt on the theoretical significance of the exponent μ . In this work, a common mechanism is proposed for the origin of both sub-aging and end of aging behavior in glassy dynamics. The mechanism combines real and configuration space properties of the state produced by the initial thermal quench which initiates the aging process.

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I. INTRODUCTION

In glassy systems, a thermal quench initiates a so called aging process, whereby physical observables, e.g. the energy, slowly change as a function of ‘age’, the term conventionally denoting the time t elapsed from the quench. In non-stationary processes, conjugated linear response and correlations functions generally depend on two time arguments, e.g. the system age t , and its value t_w at the moment where the field is switched on, or off. However, both functions appear to actually depend on a single scaling variable, namely t_{obs}/t_w^μ , where $t_{\text{obs}} \stackrel{\text{def}}{=} t - t_w$ [1, 2, 3]. The ‘observation’ time t_{obs} , (widely denoted by the symbol t in the literature) is often used in lieu of the system age as an independent time variable. The exponent μ is generally near one, and the terms *super-aging*, *sub-aging* and *pure* or *full* aging are used to discriminate between cases with $\mu > 1$, $\mu < 1$ and $\mu = 1$, respectively. Sub-aging (henceforth SA) has mainly been observed in spin-glass Thermoremanent Magnetization (TRM) data [2, 4, 5, 6], usually after subtracting a ‘stationary’ term which describes the response immediately after the field is cut.

As a quench is unavoidably carried out at a finite cooling rate, the point $t = 0$ on the time axis eludes a sharp definition in an experimental setting. Possibly as a consequence thereof, the scaling form of response functions is, in spite of a protracted debate [4, 5, 7, 8, 9, 10, 11], only partially understood. E.g. the physical significance of μ (and of the additional time scale it brings along) is unclear, even more so in the light of the recent dis-

covery that the TRM loses its t_w dependence in the limit $t_{\text{obs}}/t_w \rightarrow \infty$ [11]. This observation falsifies the long-held hypothesis that SA could be a scaling form generally applicable to linear response functions. Coined in Ref. [11], the term ‘end of aging’ (EOA) is also adopted here. It describes that, for large values of t/t_w , the t_w dependence of the TRM disappears and is replaced a simple logarithmic time decay. The term should not be construed as contradicting the fundamental unity of aging dynamics which subtends our description.

In this work, an expression for the TRM decay, Eq. (8), is derived which, depending on the value of the model parameter x , interpolates between pure aging (PA), SA and EOA behavior. Our derivation combines well known configuration and real space properties of spin glasses and supplements them with a model assumption regarding the spatial heterogeneity of the system configuration at the beginning of the isothermal aging process. Our analytical expression for the TRM decay is derived by averaging the magnetic response of independent domains over a suitable distribution characterizing their initial state. Even though the ratio t_{obs}/t_w^μ nowhere appears in the treatment, the TRM decay curves produced by our Eq. (8) can, in accordance with standard practice, be *empirically collapsed* in the SA regime using t_{obs}/t_w^μ as a scaling variable.

II. LINEAR RESPONSE AND DOMAIN HETEROGENEITY

Thermalized domains whose linear size grows with the thermal correlation length [12] are ubiquitous in aging systems with short range interactions. Real space scaling descriptions [13] rely on their properties to account for several dynamical properties, e.g. so-called ‘chaos’

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effects. In a physics context, hierarchies were brought into focus by the Parisi equilibrium solution of a mean field model [14], a solution which has inspired hierarchical models of spin-glass dynamics, e.g. [15]. However, the hierarchical nature of relaxation dynamics in complex system is a generic feature [16] which complements real space descriptions and which has e. g. been confirmed numerically by solving master equations in fully enumerated sets of states [17, 18].

Hierarchical models, see e.g. Refs. [19, 20, 21], assume that nested ergodic components [22] exist in configuration space. In simple cases, the solution of the pertinent master equations shows PA behavior [20]. For thermally activated dynamics, this result can be heuristically explained as follows: Any ergodic component of the hierarchy is at any time t indexed by a real valued ‘dynamical barrier’ $b(t)$. On the (Arrhenius) time scale $t_b(t) = C \exp(b(t)/T)$ the component is near a state of internal thermal equilibrium. The constant C is the *fluctuation time*, i. e. the smallest relevant time scale of the dynamics. Consider now a system starting in a component with vanishing initial barrier $b(t=0) \approx 0$. After aging isothermally for a time $t = t_w$, the component is characterized by a barrier $b(t_w) \propto T \ln(t_w/C)$. The dynamics on scales $t_{\text{obs}} < t_w$ has character of quasi-equilibrium fluctuations within the same component, while off-equilibrium processes involving larger components take over for $t_{\text{obs}} > t_w$. The age t_w hence separates the two dynamical regimes observed for aging systems, and constitutes the dominant time scale for $t > t_w$. From this observation, pure aging heuristically follows. A mathematically more precise route leading to the same conclusion relies on the fact that, within a hierarchy indexed by energy barriers, only thermal energy fluctuations of *record* magnitude are able to trigger irreversible changes of ergodic component, or *quakes*. Since the statistics of record-sized fluctuations in a stationary series is known analytically [23, 24], assuming that all physical changes are statistically subordinated to the quakes leads to *record dynamics* [24, 25, 26] and to analytical formulas, such as Eq. 3, for one and two-point averages of aging processes. In spite of their simplicity, the above ideas rationalize a large amount of experimental evidence, [10, 27, 28]. Yet, they neither account for SA nor for EOA scaling behaviors. In order to do so, the spatial and temporal heterogeneity of spin glasses, experimentally demonstrated by Chamberlin [29], must be properly taken into account.

In the present model, independently relaxing domains of a glassy system are all endowed with the same type of hierarchically structured configuration space. Nonetheless, their respective contributions to the overall linear response are different (albeit related) functions of time. The assumption is that domains find themselves in states characterized by different dynamical barriers at the end of the initial quench, or equivalently, at the beginning of the isothermal aging process.

The physical mechanism behind the difference is likely

related to the way in which the cooling process proceeds near the glass transition temperature, see e. g. ref. [6, 30]. Here, the spatial heterogeneity is heuristically described by a distribution of initial barriers $P(b)$. We checked that a flat distribution supported in the interval $(0, b_M^*)$ and an exponential distribution with average b_M^* lead to similar behaviors. The existence of a finite first moment of $P(b)$ seems to be the crucial feature. Since the exponential form leads to simpler closed form expressions, this form is chosen for mathematical convenience.

In summary the initial state of the aging process feature domains described by the dynamical barriers distribution

$$P(b) = \frac{1}{b_M^*} \exp(-b/b_M^*). \quad (1)$$

Let t_M^* be the Arrhenius time associated to b_M^* . As we shall see, the quantity

$$x \stackrel{\text{def}}{=} \frac{T}{b_M^*} = \frac{1}{\ln(t_M^*/C)} \quad (2)$$

controls all deviations from pure aging behavior. Note that $x > 0$, that $x \rightarrow 0$ for $t_M^* \rightarrow \infty$, and that $x \rightarrow \infty$ for $t_M^* \downarrow C$.

III. PURE AGING APPROXIMATION OF TRM DATA

The additive contribution to the magnetic response of a single domain is in the present theory given by Eq. (5). In this expression the function $M_0(t/t_w)$ describes the TRM of a domain initially in a state with vanishing dynamical barrier.

The functional form chosen for M_0 reflects that record dynamics is a homogeneous stochastic process in the single ‘time’ variable $\log(t/t_w)$. By standard arguments, all moments of the process, including the average response, admit eigenvalue expansions where $\log(t/t_w)$ replaces time. The generic term in such expansions is proportional to $(t/t_w)^{\lambda_k}$, where λ_k is the k ’th relaxation eigenvalue. In practice, the expansion can be cut after few terms and, as shown graphically in the Appendix, two terms (one term less than in Ref. [10]) already provide an acceptable parameterization of the TRM decay in the PA approximation.

Summarizing, the pure aging scaling ansatz for the TRM can be written as

$$M_0(z) = M_I + \eta(z-1) \sum_{k=1}^2 \frac{a_k}{\lambda_k} (z^{\lambda_k} - 1), \quad (3)$$

where $z = t/t_w$, and where η is the Heaviside step function, and M_I is the ‘initial’ value of the TRM, which for simplicity is treated as a parameter. According to the formula, the TRM remains constant and equal to M_I until the magnetic field is cut. The notation a_k/λ_k for the

prefactor is chosen to simplify the form of the rate of magnetization change

$$r_{\text{TRM},0}(t, t_w) = \frac{1}{t} \sum_{k=1}^2 a_k \left(\frac{t}{t_w} \right)^{\lambda_k}. \quad (4)$$

The (negative) pre-factors and exponents are for completeness tabulated in the Appendix.

IV. ORIGIN OF SUB-AGING AND END OF AGING

Let T denote the isothermal aging temperature. As mentioned, C denotes the smallest relevant relaxation time, i.e. the time associated to the smallest energy barrier in the energy landscape of a single domain. Consider now a domain characterized by the initial barrier b^* , or equivalently, by the Arrhenius time $t^* = C \exp(b^*/T)$. If $t_w < t^*$, the behavior at time $t = t_w$ remains controlled by the initial barrier b^* and the domain's contribution to the TRM correspondingly depends on t/t^* . Conversely, if $t_w > t^*$ the initial barrier has been surmounted at t_w , and the scaling variable is hence t/t_w . In real space, the size of the domain grows as a function of the dynamical barrier $b(t)$. E. g. a power-law growth in the time domain [12] corresponds to an exponential growth in $b(t)$. In our case, $b(t) = \max(T \ln(t/C), b^*)$, and domain growth is delayed up to the Arrhenius time t^* , compared to the case $b^* = 0$.

Returning to the form of the response, the contribution of a domain with initial dynamical barrier b^* is

$$m(t, t_w, b^*) = \eta(t_w - t^*) M_0(t/t_w) + \eta(t^* - t_w) M_0(t/t^*), \quad (5)$$

where η is again the Heaviside function, where M_0 is given in Eq. (3) and where $t \geq t_w$. The formula embodies the key feature of hierarchical relaxation without reference to any specific model. Secondly, it introduces spatial heterogeneity, as b^* , or equivalently, the Arrhenius time t^* , is allowed to differ across the domains. At $t_w = t^*$, the Heaviside function η switches between the two scaling forms available for the magnetic response of a single domain. If the barriers of the different domains in the system are all initially near zero, only the first term contributes, and the pure aging behavior given by $M_0(t/t_w)$ goes through at the macroscopic level. In the general case, the TRM decay takes the form

$$M(t, t_w) = M_0(t/t_w) \int_0^{T \ln(t_w/C)} P(b) db + \int_{T \ln(t_w/C)}^{T \ln(t/C)} M_0 \left(\frac{t}{C} e^{-b/T} \right) P(b) db + M_1 \int_{T \ln(t/C)}^{\infty} P(b) db, \quad (6)$$

where $P(b)$ is the probability density for a domain with barrier in the initial state.

Inserting Eq. (1) into Eq. (6), and using simple alge-

braic manipulations, one arrives at

$$M(t, t_w) = M_1 \left(\frac{t}{C} \right)^{-x} + \left(1 - \left(\frac{t_w}{C} \right)^{-x} \right) M_0(t/t_w) + x \left(\frac{t}{C} \right)^{-x} \int_1^{t/t_w} M_0(z) z^{x-1} dz. \quad (7)$$

Using the parameterization of M_0 given in Eq. (3), the last expression becomes

$$M(t, t_w) = M_0(t/t_w) + \left(\frac{t_w}{C} \right)^{-x} \sum_{i=1}^2 \frac{a_i}{\lambda_i + x} \left[\left(\frac{t}{t_w} \right)^{-x} - \left(\frac{t}{t_w} \right)^{\lambda_i} \right]. \quad (8)$$

Pure aging is achieved in the limit $x = \infty$, i.e. when all initial barriers are equal to zero with probability one. Sub-aging is present for *intermediate* values of x . Let now λ_2 be the largest of the two decay exponents characterizing the pure aging regime. If and only if $x < -\lambda_2$, the asymptotically dominant contribution to the TRM for large t is proportional to $(\frac{t}{C})^{-x}$. To bear this out, we first re-write our last equation as

$$M(t, t_w) = M_0(t/t_w) + \left(\frac{t}{C} \right)^{-x} \sum_{i=1}^2 \frac{a_i}{\lambda_i + x} \left(1 - \left(\frac{t}{t_w} \right)^{\lambda_i + x} \right). \quad (9)$$

The pure aging term $M_0(t/t_w)$ decays the fastest and can be neglected. In what remains, the t_w dependent term having the slowest decay is $(t/t_w)^{\lambda_2 + x}$. In order for the EOA behavior to set in, this term must be much smaller than one. E.g. a relative deviation of the TRM curve from EOA equal to 1/10 is reached at time

$$t_{\text{EOA}} = (10)^{\frac{1}{|x+\lambda_2|}} t_w. \quad (10)$$

Since $\frac{1}{|x+\lambda_2|}$ is very large when $x + \lambda_2 \approx 0$, the model predicts that EOA may occur on a time scale which diverges very rapidly with t_w . This is qualitatively in accord with the experimental observations of Ref. [11]. Secondly, when the exponent x is numerically small, the expansion $(t/C)^{-x} = 1 - x \ln(t/C) + \mathcal{O}((x \ln(t/C))^2)$ is applicable, and the TRM decays in a nearly logarithmic fashion for a wide range of t , also in accord with the experimental findings.

V. ON t_{obs}/t_w^μ SCALING

Equation (8) features a clear sub-aging behavior without any reference to the widely used scaling variable t/t_w^μ . Nevertheless, model generated TRM data can be empirically scaled in the traditional manner for intermediate values of t and t_w . This is checked numerically (*i*) by evaluating Eq. (8), with $C = 1$, $t_M^* = 10$ and with all other parameters given in Table. I, and (*ii*) by

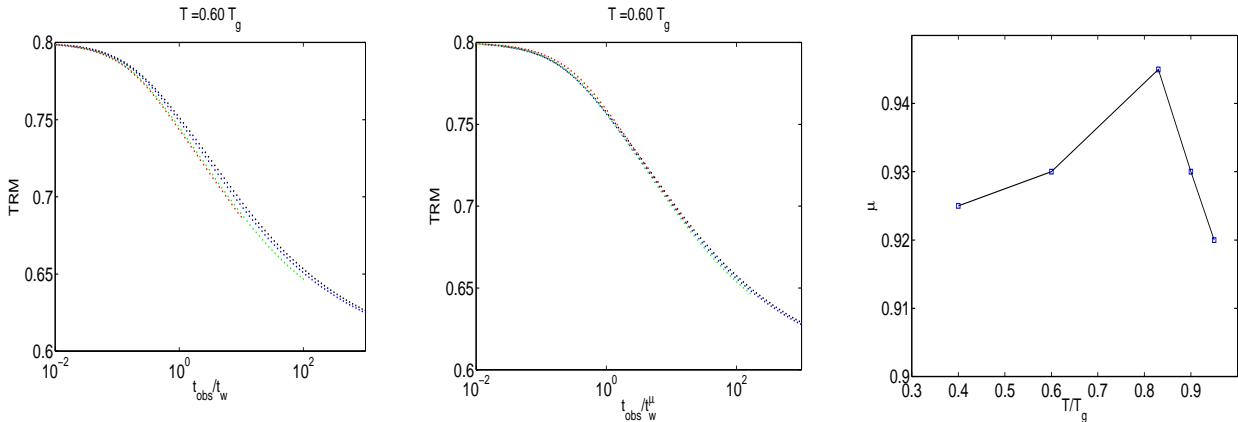


FIG. 1: (Color on line) The Thermoremanent Magnetization calculated according to Eq. (8) is plotted for $t_w = 50, 100, 1000$ and 10000 (black, blue, green and red) and for $T = 0.60T_g$ versus t_{obs}/t_w , (left figure), and versus t_{obs}/t_w^μ , (middle). The left figure shows that sub-aging is present, and the middle figure that the standard scaling procedure collapses the data. Scaling plots for other temperatures are also performed (not shown). In each case a μ value is estimated as the one providing the best collapse. In the rightmost figure, the empirical values of μ are plotted versus T/T_g , showing a clear maximum at $T/T_g = 0.83$. The line is only a guide to the eye.

scaling the curves obtained as usually done for experimental data. The left panel in Figure (1) only confirms that t_{obs}/t_w scaling is not satisfactory for the parameter values utilized. The four curves plotted all pertain to $T = 0.6T_g$. The values of t_w used are $t_w = 50, 100, 1000$ and 10000 . The exact same data are shown in the second panel of the same figure. They are now plotted versus t_{obs}/t_w^μ , with the value of μ chosen as the one judged to produce the best data collapse. Additional curves (not shown) were similarly obtained by evaluating Eq. (8) for $T/T_g = 0.4, 0.6, 0.9$, and $T = 0.93$. The empirical μ values thus obtained gauge how close the TRM is to pure aging. These values are plotted versus T/T_g in the right panel of the same figure (the line is only a guide to the eye). Interestingly, μ versus T peaks at $T/T_g = 0.83$, the very temperature where μ is experimentally closest to one [5].

In summary, Eq. (8) fully contains the standard sub-aging behavior widely seen in spin glasses. Furthermore, it demonstrates that the applicability of t_{obs}/t_w^μ scaling does not *per se* endow the exponent μ with physical significance, which is plainly absent in our case.

VI. SUMMARY AND OUTLOOK

In this work, the known scaling properties of off-equilibrium linear response functions in spin glasses have been accounted for by combining two aspects of complex dynamics: the hierarchical relaxation of independently thermalizing domains, coupled with the spatial heterogeneity of the initial domain configurations, as defined by their initial dynamical barriers. These barriers would uniformly vanish for a system conforming to pure aging scaling behavior. Our analysis relies on generic properties of complex dynamics, and should therefore be widely ap-

plicable to glassy systems with short range interactions. These might include quantum spin glasses, whose critical behavior has recently been investigated [31, 32], and irrespective of whether a true equilibrium phase transition exists [32] or not [31].

The distribution of initial dynamical barriers plays a pivotal role in the theory. Arguably, its form depends on the cooling protocol, e.g. fast cooling could give a distribution more sharply peaked at zero, and lead to a relaxation scaling form closer to pure aging. The width of the initial barrier distribution is expressed by the exponent x , which is *experimentally accessible* as the logarithmic slope of the TRM decay for very large values of t/t_w , i.e. in the dynamical regime where the t_w dependence of the data is absent. It should therefore be possible to empirically study, via x , how the initial cooling protocol affects the distribution of initial barriers and, indirectly, the subsequent relaxation dynamics.

T/T_g	a_1	λ_1	a_2	λ_2
0.40	-0.0878	-2.7575	-0.0289	-0.1869
0.60	-0.0981	-3.0945	-0.0462	-0.2609
0.83	-0.1365	-2.9016	-0.0527	-0.3102
0.90	-0.1309	-3.2785	-0.0418	-0.3098
0.95	-0.1117	-3.4737	-0.0296	-0.3495

TABLE I: The first column contains the ratios of the isothermal aging temperature T at which the measurements are taken to the critical temperature T_g . The other columns contain the pre-factors and exponents of the two power-law terms appearing in Eq. (3). All values are obtained by fits (not shown) of quality similar to Fig. (2).

VII. APPENDIX

We describe in this Appendix how the parameter values entering Eq.3 are estimated by fitting to experimental TRM data. The data are obtained according to a standard procedure: a Cu_{0.94}Mn_{0.06} spin glass sample

is rapidly quenched to a temperature $T < T_g$ in the presence of a small magnetic field. The field is cut at time $t = t_w$, and the magnetization decay is then recorded [2, 4, 5, 6] for $t > t_w$.

The parameters shown in Table (1) are used *empirically determine*, on the basis of Eq. 8, the SA exponent $\mu(T)$. The small deviation of the experimental data from the pure aging form given in Eq.3 implies, of course, a small systematic error.

Of special importance are the values of the dominant exponent λ_2 which are listed in the last column of the table: According to Eq. 10, the quantity $\lambda_2 + x$ determines the time scale for the onset of *EOA* behavior.

Figure 2 is scaling plot of the rate of (de-) magnetization multiplied by the system age, versus the scaling variable t/t_w . At the aging temperature $T = 0.83$ the empirical sub-aging exponent μ is very close to one [4, 5] and the data conform reasonably well to a PA ansatz. The approximation is worse, but still usable, at other aging temperatures and all data can be fit reasonably well by the full aging formula 3.

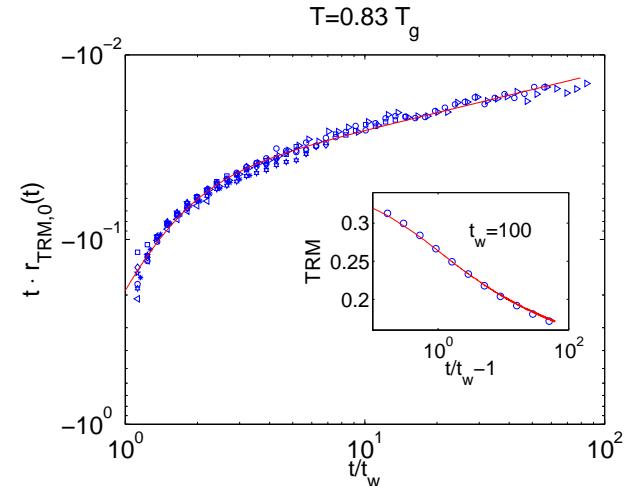


FIG. 2: (Color on line) The TRM decay rate, multiplied by the age t is plotted versus t/t_w for $T/T_g = 0.83$ and $t_w = 50$ (right pointing triangles), 100 (circles), 300 (squares), 630 (diamonds), 1000 (pentagrams), 3600 (hexagrams), 6310 (asterisks) and (10000) (left pointing triangles). The line is given by Eq. (4). The insert compares the TRM decay measured at $t_w = 100$ s (red line), with the theoretical estimates (blue circles) obtained by Eq. (3).

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